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Measurement of Dynamics in Strontlum Magnetc-Optical Trap

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$L = (n^2 + 2)/3$, n is the refractive index of medium.

Another indication of the role of Q-band in resonance enhancement of TPA can be found from the TPA spectrum. We showed that the frequency of one-photon intermediate transition, which can be found from (1), as

$$\nu_{i0} = \nu_p + 2\frac{\sigma_2}{d\sigma_2/d\nu_p}, \qquad (2)$$

coincides well with the real maximum of the Q-band.

We have also calculated the σ_2 value for ZnOEP directly from (1), by taking all other parameters from independent measurements, and obtained a 10% correspondence with our experimental value.

In our paper we will show how the present relationship facilitates a search for new porphyrins with greatly enhanced nonlinear properties.

References

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QTuB

8:00 am–9:45 am
Room: 202

High Resolution Spectroscopy and Fundamental Measurements

Kurt E. Gibble, Penn State Univ., USA, Presider

QTuB1 Invited **8:00 am**

Quenched Narrow-Line Cooling in Neutral Calcium

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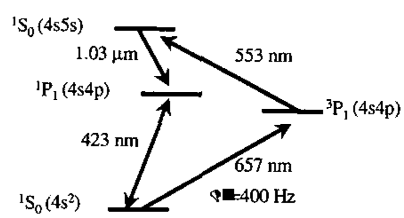
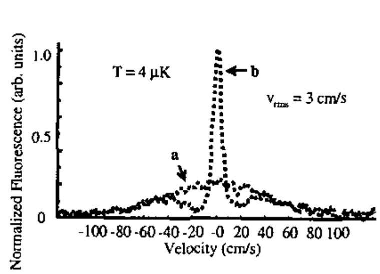
The successful laser cooling of alkali elements to microkelvin temperatures has led to a host of important applications ranging from atomic interferometry to quantum degenerate gases. The alkaline-earth elements show similar promise, including original applications that exploit their unique atomic structure. However, many of these applications are hindered by warm (Doppler-limited) trap temperatures of typically a few mK, which are a consequence of the alkaline-earth ground-state structure. Thus, strategies for second-stage cooling of these atoms need to be developed. Here we demonstrate a cooling scheme for neutral Ca that has attained microkelvin temperatures and is applicable to other alkaline-earth elements. This large reduction in temperature should significantly improve absolute frequency measurements for our Ca-based optical frequency standard, for which the most recent result was limited (with an uncertainty of 26 Hz) primarily by the residual velocity of the laser-cooled atomic sample.[1]

A second-stage cooling scheme for another alkaline-earth atom, Sr, used an intercombination line and achieved temperatures at the recoil limit.[2] The corresponding transition in Ca($^1S_0 \rightarrow {}^3P_1$ at 657 nm) is 20 times narrower, making it a good choice for our frequency standard, but unfortunately too weak to produce effective cooling for the high initial atom temperature. Nonetheless, we can take advantage of the high velocity selectivity of this narrow transition by implementing an approach first demonstrated with trapped ions, which uses quenching of the long-lived excited state via another transition in order to accelerate the cooling process.[3] In our version we start with a magneto-optic trap based on the $^1S_0 \rightarrow {}^1P_1$ transition at 423 nm. With this apparatus we can load 10^7 atoms in ~10 ms with a resultant atomic temperature of 2 mK. We then implement a second stage of cooling that uses the clock transition to drive chosen velocity classes of atoms towards zero velocity and quenches the $^3P_1$ excited state with 552 nm light (see Fig. 1) to reduce the decay time. In our first demonstration we used multiple sets of counter-propagating, suitably detuned pulses of 657 nm light followed by quenching pulses (effective decay time of 50 μs), and were able to reduce the atom cloud temperature in one dimension to 4 μK.[4] A recent increase in quenching laser power enabled more cooling cycles. We were also able to improve the net transfer efficiency from 15 to 25% by chirping the 657 nm pulses towards the center frequency of the transition during the cooling process. (See Fig. 2.) We note that a group at Physikalisch-Technische Bundesanstalt has demonstrated quenched cooling and trapping for Ca in three dimensions (3D) using spectrally-broadened 657 nm light and quenching light at 453 nm,[5] which differs from our use of pulsed light fields.

We are presently investigating various schemes for quenched cooling in 3D, which should give sub-recoil temperatures and higher transfer efficiencies. Such samples should produce significant improvement in the performance of optical frequency standards as well as open the door to other applications, enabling efficient loading of dipole traps and higher phase-space densities.



QTuB1 Fig. 1. Relevant energy level diagram for Calcium.



QTuB1 Fig. 2. a) Velocity distribution of initially trapped and cooled Ca atoms. b) Final velocity distribution after 15 chirped and 10 stationary second-stage cooling cycles. Each cycle consisted of two counter-propagating, temporally separated, 5 μs 657 nm pulses follow by 20 μs of 552 nm light. A 40 μs post-cooling pulse of 552 nm light was used to pump the remaining atoms back to the ground state.

References

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QTuB2 **8:30 am**

Measurement of Dynamics in Strontium Magneto-Optical Trap

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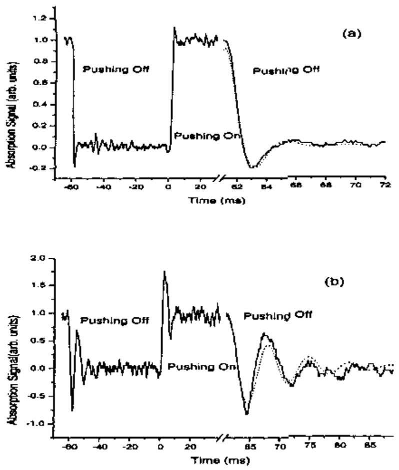
Recently, laser-cooled alkaline earth atoms have become prime candidates for constructing optical frequency standards and studying cold collisions. Since the even isotopes have no hyperfine structure, they provide an ideal system for testing Doppler-cooling theory. (Alkali atoms are subject to sub-Doppler cooling mechanisms.) We have measured the spring constant (k) and damping coefficient (α) in a Strontium MOT by observing the damped oscillation response of the trapped-atom location to a square-wave chopped pushing beam.

The experiment consists of a Sr vapor cell MOT using the 461 nm $^1S_0$-$^1P_1$ cycling transition to cool and trap. The MOT is a standard six-beam σ^+-σ^- configuration with a magnetic quadrupole field. We use an on-resonance beam to push the trapped atoms away from the trap center by 10–20% of the cloud diameter. In addition, a weak on-resonance probe beam, focused off the trap center, propagates perpendicular to the pushing beam. During the chopping cycle of the pushing beam, the step response of the trapped atoms is observed in the probe absorption signal, as shown in Fig. 1. The motion of the trapped atoms is clearly underdamped in Fig. 1b, differing from the strongly overdamped motion of a previous alkaline-metal atom MOT.[1] We have also measured the dependences of k and α on the



QTuB2 Fig. 1. Probe absorption by the trapped atoms during the chopping cycle of the pushing beam. Notice the expanded time scale after the break. The fitting curves are shown as the dotted lines after the break. The total intensity of the trapping beam is (a) 21 mW/cm^2, and (b) 9 mW/cm^2, the detuning of the trapping beam is −40 MHz and the magnetic field gradient is 64 G/cm. The least-square fit to the data yields k = 3.5×10^{-19} (N/m) and $\alpha = 2.2 \times 10^{-22}$ (N.s/m) in (a), and k = 1.3×10^{-19} (N/m) and $\alpha = 0.42 \times 10^{-22}$ (N.s/m) in (b).

magnetic field gradient and the intensity and detuning of the trapping beam. Preliminary experimental values of k and α are smaller than those predicted by standard Doppler theory.[2] It is worth noting that the temperature of the atom cloud is intensity dependent, also in contradiction with standard Doppler theory.[3] Since during the cooling cycle trapped atoms slowly leak from the excited $^1P_1$ state through $^1D_2$ to $^3P_2$ and are then lost, the simple two-level Doppler theory is not complete for this system. At present, a modified semi-classical Doppler theory is being developed to account for the resulting variations in k and α.

Since the temperature can be determined by the measured spring constant and the trap size, this experiment also offers a new possibility of temperature measurement. We will further study the dynamics of the trapped atoms after second-stage Doppler cooling, using the 689 nm narrow, spinforbidden $^1S_0$-$^3P_1$ intercombination line. Since the 689 nm photon recoil frequency shift is greater than the cooling transition linewidth, a full quantum mechanical cooling theory needs to be explored.

References

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QTuB3 **8:45 am**

Four Photon Coherent Interaction Applied to Long Term Stabilization of a Femtosecond Clock

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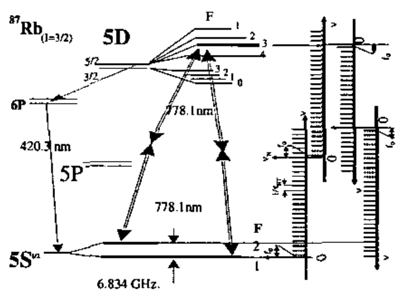
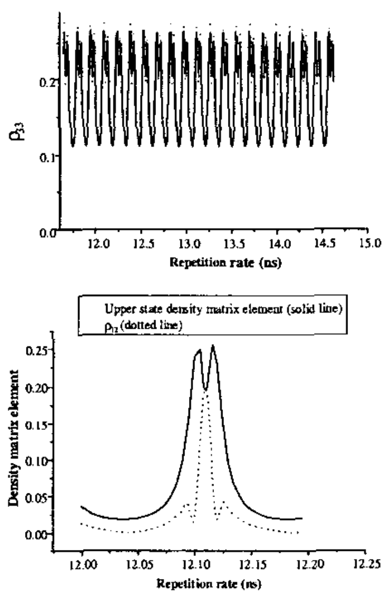
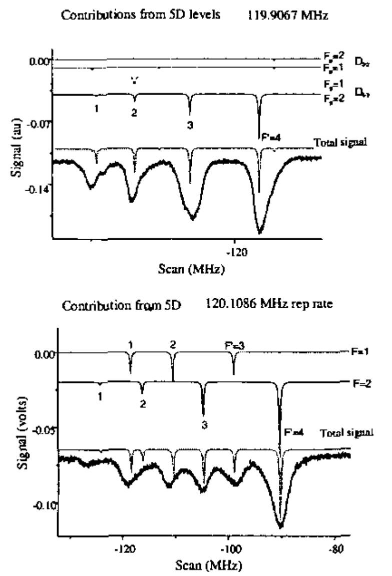
The general objective of this work is to provide a stable and accurate frequency standard affordable in any physics laboratory, using the regular frequency comb provided by a mode-locked laser.[1,2] The frequency of the tooth m of the comb is given by $\nu_m = \nu_0 + m/\tau_{RT}$ where τ_{RT} is the round-trip time of the pulse in the laser cavity, and ν_0 is the zero-offset frequency of the comb. We have previously demonstrated that both the repetition rate and the zero-offset can be stabilized to a fractional instability of $\approx 2 \times 10^{-12}$ in less than 800 ms,[3] limited by the clock used for the RF counters used in that measurement. For accuracy and long term stabilization, one should (i) define the RF frequency from a division of the optical frequency, and (ii) control the drift of the reference cavity with an atomic standard. We present a new approach to stabilize both repetition rate and zero-offset of the comb by locking the average frequency to a two-photon resonance of a rubidium transition, and the repetition rate to a dark line resonance. The particular transitions involved are sketched in Fig. 1. Carrier frequency stabilization is made on the two-photon $5D^{5/2} \rightarrow 5S^{1/2}$ transition, in counter-propagating (Doppler free) geometry.



QTuB3 Fig. 1. Level structure of rubidium. The frequency comb of the fs laser climbing up and down the λ structure is shown on the right.



QTuB3 Fig. 2. Left: steady-state population of the upper state ρ_{33} as a function of round-trip time, for excitation by a trains of mode-locked pulses. The pulse area is 0.5. The detail of a dark line resonance is shown in the center. The solid line is the upper state population ρ_{33}; the dotted line the coherence between the split ground state ρ_{12}.



QTuB3 Fig. 3. Three two-photon fluorescence spectra of rubidium, taken for increasing laser repetition rates.

With a ground state splitting of 6.834682 GHz, this transition constitute a four-photon Λ structure, each branch of the Λ being a two-photon transition from one of the ground states. The density matrix equations for the four-photon interaction with the two-photon Λ structure were solved numerically, using a Butcher predictor-corrector method, for a periodic pulse trained tuned to the two-photon transition, $5S^{1/2}(F = 2) \rightarrow 5D^{5/2}(F = 3)$, as illustrated in Fig. 1. Figure 2 shows a plot of the population of the upper state as a function of repetition rate, after a steady state has been reached (i.e. 1000 round-trips). For particular repetition rates, both branches of the Λ structure are resonant, resulting in a decrease of the upper state population (ρ_{33}), and at the same time the off-diagonal matrix element connecting the levels of the split ground state ρ_{12} peaks (dotted line). This "dark resonance" is Doppler free in travelling wave geometry, and will enable us to provide an error signal to stabilize the repetition rate to a submultiple of the hyperfine splitting of 6.834682 GHz, while the carrier frequency is locked to one of the two-photon transitions in the Λ structure.

"Doppler free" two-photon spectroscopy of rubidium was performed with the mode-locked